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Drone-Informed Smart City Planning for Sustainable Urban River Corridors

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Abstract.

Urban riverbanks in rapidly developing cities face significant challenges, including land scarcity, informal settlements, and environmental degradation. This study explores integrating drone-based mapping, geospatial analysis, and smart environmental governance to regenerate the Brantas River corridor in Malang, Indonesia. High-resolution imagery captured using the DJI L1D-20c sensor produced orthomosaics and Digital Surface Models (DSMs), revealing substantial discrepancies between planned and actual land use. More than 60% of the riverbank was occupied by informal housing, and vegetation cover was reduced to below 20% of the designated green buffer. By overlaying drone outputs with thematic GIS data, the study identified priority areas for substituting green spaces and ecological restoration. The findings informed the development of a Management Information System (MIS) aligned with Indonesia's One Map Policy and Satu Data Indonesia initiative, facilitating real-time monitoring and data transparency. A pentahelix collaboration model, involving government, academia, industry, community, and media, was applied to enhance participatory governance and ensure inclusivity in planning outcomes. The resulting Smart River Regeneration Framework integrates three interrelated layers: ecological restoration, spatial–architectural restructuring, and digital governance. This integrative approach demonstrates how drone and smart city technologies can support evidence-based decision-making, adaptive design, and community empowerment. Overall, the study presents a replicable model for environmentally intelligent and socially inclusive urban transformation in riverine contexts of developing cities.

Keywords: Drone mapping, Geospatial analysis, Pentahelix collaboration, Riverbank regeneration, Smart governance, Sustainable city, Urban green space

1. Introduction

Rapid urbanization in Indonesia and many other developing countries has increasingly driven the growth of high-density settlements along river corridors, which often lie outside the formal planning frameworks of cities (Gunawan et al., 2022). These riverbank zones typically become areas of informal settlement due to limited land, proximity to economic centres, and lax enforcement of land-use controls (Alzamil & Arabia, 2018). Particularly in the case of the city of Malang, despite a well-articulated urban development plan (Satuan Wilayah Pengembangan Malang Tengah) and a municipal Green Open Space Master Plan for 2012-2032, the areas along the Brantas River (DAS Brantas) remain under-regulated and underserved. There is a marked gap between the spatial plan and the actual land-use realities along the riverbank, characterized by a decline in vegetative cover, encroachment of dense settlements, and a lack of quality environmental buffering.

From a planning and governance standpoint, river-corridor areas like these should logically be designated as High Control Zones (HCZ)—serving as ecological buffers and substitutes for urban green open space (RTH). However, in practice, this ideal often remains unfulfilled due to insufficient spatial data, weak regulatory enforcement, and a limited mechanism for meaningful public participation (Setiadi & Kusliansjah, 2021). At the same time, the advent of digital technologies, big data, and the Internet of Things (IoT) in the era of Industry 4.0 / Society 5.0 offers new opportunities for implementing what is often called Smart City Planning—an approach that emphasises integrative data, real-time monitoring, and stakeholder-inclusive governance (Bakri & Kasim, 2018). Spatial technologies such as drones and LiDAR further support this shift by enabling high-resolution mapping and monitoring of urban and environmental systems (Setyawan et al., 2022).

In view of these dynamics, the riverbank settlement along the Brantas River in Malang City represents a compelling case study. It illustrates the intersection of dense urban habitation, ecological risks in river corridors, and the potential for digital/planning innovation. The settlement context—characterised by informal housing, vulnerability to flooding and erosion, and constrained access to green space—makes it especially relevant. Studies from other Indonesian cities confirm that water-adjacent settlements frequently lack formal services and regulatory protection, thereby exacerbating vulnerabilities (Mukaromah et al., 2025; Setiadi et al., 2025).

This study therefore sets out with three key objectives: (i) to identify the spatial and governance challenges in managing a densely settled riverbank area (Jodipan–Brantas corridor, Malang City); (ii) to explore how principles of Smart City Planning—especially drone-based spatial mapping, data integration, participatory governance—can support sustainable environmental management and the provisioning of green open space in a HCZ context; and (iii) to develop a conceptual framework for spatial planning, design, and governance of dense riverbank settlements based on real-time spatial data, stakeholder collaboration (pentahelix model), and smart governance. In doing so, the paper aims to contribute to both the academic literature on urban planning for riverfront settlements and the practical agenda of sustainable urban environmental governance in the digital age.

2. Literature Review

2.1 Urban Density and Riverbank Settlements

Dense settlements along riverbanks present environmental, social, and infrastructure challenges. Studies in Indonesia show that riverbank settlements are often overlooked in formal city plans, leaving sanitation, infrastructure access, and the environment vulnerable. For example, a study in Palembang showed that the physical form of houses and the culture of riverbank living need to be preserved in conservation plans (Oktarini et al., 2023). Studies also show that developing green open spaces on riverbanks can improve the quality of life and reduce the risk of flooding (Abed, 2024).

2.2 Smart City Planning and Environmental Governance

The smart city concept has moved beyond mere technological deployment to emphasize system integration, data transparency, and multi-stakeholder collaboration as core elements of urban governance. Foundational definitions by Caragliu, Del Bo, and Nijkamp (2011) frame a

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smart city as one that leverages human and social capital, together with modern ICT, to enhance urban performance, service efficiency, and quality of life, stressing that technology must be combined with social and institutional capacity (Caragliu et al., 2011).

In developing-country contexts, smart city initiatives are increasingly viewed as tools to achieve sustainability rather than ends in themselves. Systematic reviews indicate that successful implementation necessitates concurrent social, regulatory, and capacity reforms (e.g., governance, digital inclusion, financing) in addition to technology alone. At the same time, policy roadmaps (national/regional digital agendas) signal a strategic shift toward integrating digital infrastructure in long-term urban development planning (Tan & Taeihagh, 2020).

From an environmental governance perspective, smart city approaches emphasize real-time spatial monitoring (utilizing IoT, sensors, drones, and LiDAR), integrated geospatial information systems, and Decision Support Systems (DSS) that combine diverse data streams (the Big Data 3V: variety, velocity, and volume). These capabilities enable faster detection of land-use change, proactive flood and ecosystem risk management, and more transparent, participatory decision-making — transforming traditional planning into adaptive, evidence-based governance (Ahvenniemi et al., 2017; Science & Studies, 2007).

2.3 Drone Mapping and Geospatial Technology in Urban Planning

The advancement of drone-based mapping and aerial imagery has revolutionized the acquisition of spatial data in urban planning, particularly in high-density and riverbank areas. Drones can capture high-resolution images and generate detailed orthomosaics and 3D surface models within short timeframes, making them essential for monitoring dynamic urban changes. Compared to traditional surveying, unmanned aerial vehicles (UAVs) provide a cost-effective, flexible, and repeatable solution for capturing geospatial data in inaccessible or informal urban zones (Colomina & Molina, 2014; Nex & Remondino, 2014). These advantages enable planners to conduct rapid assessments of land use, infrastructure, and environmental conditions with improved temporal accuracy.

Recent studies have integrated drone imagery with deep learning and computer vision techniques to identify informal settlements and urban morphologies. The URBAN-i model, for instance, demonstrates how convolutional neural networks (CNN) can automatically classify and map informal housing areas using aerial imagery. Such integration of artificial intelligence with remote sensing enhances the detection of urban patterns and socioeconomic vulnerabilities. Moreover, the use of UAV-based photogrammetry combined with machine learning has improved urban feature extraction, including building footprints, vegetation indices, and impervious surface mapping

Beyond mapping, drones play a crucial role in Decision Support Systems (DSS) for urban management and environmental monitoring. Equipped with IoT sensors and LiDAR technology, drones can collect spatial and environmental parameters, including temperature, humidity, vegetation health, and flood risk. These datasets are integrated into GIS platforms to support decision-making related to land-use change, flood mitigation, and infrastructure resilience (Adao et al., 2017). In riverbank zones, drone mapping is particularly valuable for detecting illegal settlements, monitoring vegetation cover, assessing soil erosion, and planning green buffer zones that align with sustainable urban development strategies

2.4 Participatory Governance, Pentahelix Model, and Urban Green Space

Participatory governance has become a crucial pillar in sustainable urban development, particularly in densely populated and informal riverbank settlements. The pentahelix collaboration model, which integrates government, academia, business, community, and media, encourages the co-creation and co-management of urban spaces. Such a model ensures that decision-making processes are inclusive and knowledge-based, bridging top-down urban planning with bottom-up local wisdom. In Indonesia, several initiatives, such as Kota Kita in Surakarta, have demonstrated the value of participatory urban mapping and public engagement in reclaiming riverbank spaces and redesigning them as inclusive public areas (Kota Kita, 2021). This approach strengthens community ownership while promoting adaptive governance in rapidly urbanizing contexts.

Urban green spaces (UGS) serve not only ecological but also socio-economic and cultural functions. They improve air quality, mitigate the urban heat island (UHI) effect, enhance biodiversity, and promote public well-being (Pauleit et al., 2019). Studies have shown that participatory green space design increases users' sense of belonging and enhances long-term maintenance success. Moreover, the inclusion of local actors through participatory approaches leads to more context-sensitive solutions that reflect cultural and environmental realities in developing cities. Therefore, integrating the pentahelix governance model into smart city planning offers an effective pathway to link digital innovation with sustainable environmental management.

In this context, riverbank areas should be reimagined not only as flood-control zones but as High Control Zones (HCZ) that function as ecological buffers and social commons. Utilizing drone-based spatial data, IoT environmental monitoring, and participatory digital platforms can support adaptive management of these zones. This model aligns with the global agenda for smart and sustainable cities, emphasizing inclusivity, resilience, and data-driven environmental governance (Ahvenniemi et al., 2017).

2.5 Gap Analysis

Despite extensive research on smart city development and green urbanism, several research gaps remain unaddressed. First, there is a lack of empirical studies that explicitly connect drone-based spatial mapping with the design and governance of riverbank settlements in developing countries. Second, few frameworks integrate real-time spatial data, smart city planning, and participatory governance into a single operational model for dense urban environments. Third, the conceptualization of High Control Zones (HCZ) as ecological substitutes for public green spaces in riverine urban areas remains underexplored, particularly in mid-sized Indonesian cities such as Malang.

This study addresses these gaps by proposing an integrated framework that combines drone mapping, smart city planning principles, and participatory governance through the pentahelix approach. The framework aims to enhance environmental intelligence, improve data-driven spatial planning, and strengthen community-based resilience along riverbank settlements.

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3 Methodology

3.1 Research Approach

This research employs a qualitative descriptive approach, combined with quantitative spatial analysis, utilizing drone mapping data and geospatial information systems (GIS). The three main stages of the research are: (i) spatial data collection and mapping using drones; (ii) spatial thematic analysis using GIS to assess physical, environmental, and spatial conditions; (iii) development of a conceptual framework for smart city design and governance for riverbank areas.

3.2 Study Location

The study location is the Jodipan riverbank area in Malang City, which is part of the Brantas Watershed corridor within the Central Malang Development Area. This location was chosen because of its combination of characteristics: dense settlements, proximity to the river, and high potential for green space substitution (approximately 63% of the city's total green space is located in the river corridor).

Figure 1. Green Space in The River Coridor

Figure 2. The Jodipan riverbank area in Malang City

3.3 Data Collection

The data collection process was designed to integrate spatial, regulatory, and participatory inputs into a comprehensive framework for smart city planning. This mixed-method approach combines technological precision with contextual understanding to ensure that the mapping and design outcomes reflect both environmental realities and social dynamics. Primary data were acquired through drone-based surveys, while secondary data were obtained from geospatial databases, thematic maps, and policy documents. Stakeholder participation was also included to validate data interpretation and ensure inclusivity in the planning process.

The following datasets were collected:

1. Drone Aerial Mapping: High-resolution aerial data were captured using a drone equipped with an L1D-20c (10.26 mm) camera. The flight missions produced orthomosaics, Digital Surface Models (DSMs), and land cover maps, which served as the spatial foundation for subsequent analysis and design simulations. These data provided critical information on building density, vegetation distribution, and the physical morphology of the riverbank settlements.
2. GIS Thematic Data: Secondary geospatial datasets were compiled, including topography and contours, river and waterway networks, land use patterns, flood vulnerability zones, vegetation cover, infrastructure layouts, geology and soil characteristics, health and sanitation indicators, socio-economic variables, disaster

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risk zoning, land assets and tenure status, and biodiversity mapping. The data were harmonized within a GIS environment based on the thematic map classification table developed for this study.

3. Policy and Regulatory Documentation: A comprehensive review of urban policy instruments was undertaken, including the 2012–2032 Green Open Space (RTH) Masterplan, the Malang City Spatial Planning Regulation (RTRW), and specific local ordinances governing watershed area utilization and settlement control. This review ensured alignment between the proposed design interventions and existing urban governance frameworks.
4. Stakeholder Interviews and Participation: Semi-structured interviews were conducted with relevant institutions such as the City Planning Agency (Bappeda), the Environmental Service (DLH), local community representatives, and private sector actors involved in mapping and geospatial technology. These engagements provided qualitative insights into institutional coordination, public participation mechanisms, and technological readiness for implementing drone-based smart city planning in Malang.

3.4 Data Analysis

Following data collection, a multi-layered analytical framework was employed to synthesize spatial, environmental, and governance dimensions. The analytical process was designed to bridge the gap between empirical spatial data and conceptual modeling for sustainable riverbank settlement design. The integration of geospatial analysis, smart city principles, and participatory governance provided the basis for developing an adaptive planning model suitable for dense urban riverfront areas.

The data analysis involved three interrelated stages:

a. GIS Analysis:
Geographic Information System (GIS) analysis was conducted through thematic map overlays to identify spatial discrepancies between existing plans and actual conditions. This stage focused on detecting areas of ecological degradation, settlement overexpansion, and reduced green coverage along the riverbanks. The overlay method allowed the visualization of settlement density, vegetation cover, flood-prone zones, and potential sites for green space substitution. The spatial output informed the delineation of High Control Zones (HCZ)—zones prioritized for ecological restoration, urban greening, and settlement revitalization.

b. Smart City Conceptual Analysis:
A conceptual framework for smart environmental governance was developed based on the Big Data principles of the 3Vs (Variety, Velocity, Volume). This framework emphasizes data integration from multiple sources—drone imagery, IoT sensors, and participatory mapping—into a unified Management Information System (MIS). The analytical framework also embeds the pentahelix collaboration model, aligning the roles of government, academia, private sector, community, and media in an interoperable Decision Support System (DSS). The DSS aims to enhance data-driven decision-making, transparency, and cross-sector coordination in urban riverbank management.

c. Design Model Development:
Based on spatial mapping and analytical findings, an adaptive reuse design model was formulated. This model integrates river normalization strategies with architectural and urban design interventions, aiming to enhance environmental performance while

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improving livability in dense settlements. The design approach applies smart city principles to reconfigure informal riverside housing into structured, sustainable, and inclusive environments. The final design concept is envisioned to be compatible with existing smart city initiatives, serving as a prototype for other riverbank settlements in Indonesian cities.

4 Result and Discussion

4.1 Drone-Based Mapping and Spatial Analysis

The drone-based survey conducted using the DJI Mavic 2 Pro equipped with an L1D-20c (10.26 mm) camera successfully captured ultra-high-resolution orthomosaic imagery and Digital Surface Models (DSM) of the Brantas River corridor in Jodipan, Malang. Through Structure-from-Motion (SfM) photogrammetry, the drone flight produced centimeter-level accuracy in visualizing the topography, building density, vegetation distribution, and morphological changes along the riverbank. Compared with the existing Malang City spatial datasets and the 2012–2032 Green Open Space Masterplan, the results revealed substantial discrepancies between planned and actual land-use conditions.

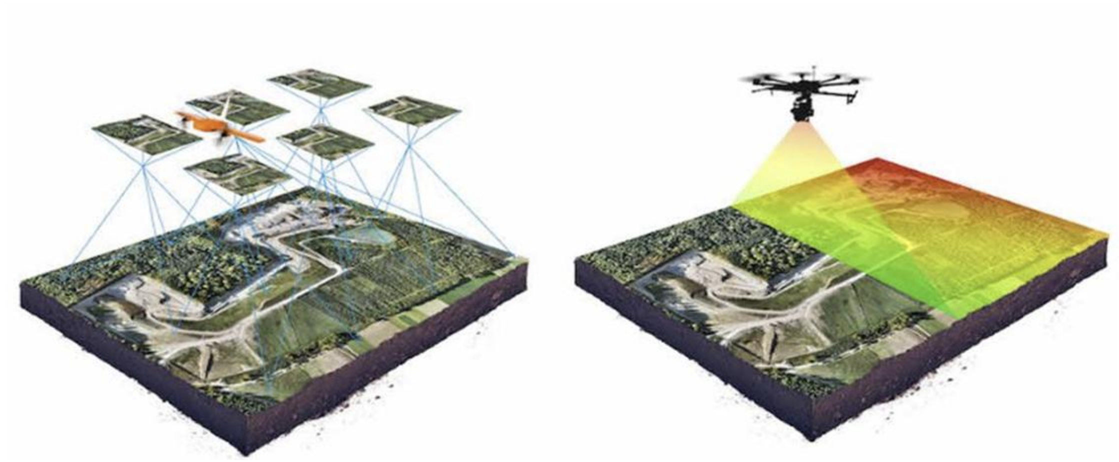

Figure 3. Illustration of drone mapping process

The orthomosaic image showed that approximately 60% of the total riverbank zone within the study area is occupied by high-density residential buildings, primarily informal settlements that extend up to the river's edge. The remaining land is fragmented into small open spaces, pedestrian alleys, and narrow vegetation patches. Based on Normalized Difference Vegetation Index (NDVI) calculations derived from the orthomosaic, the vegetation index ranged from 0.15 to 0.25, indicating sparse greenery and a weak ecological buffering capacity.

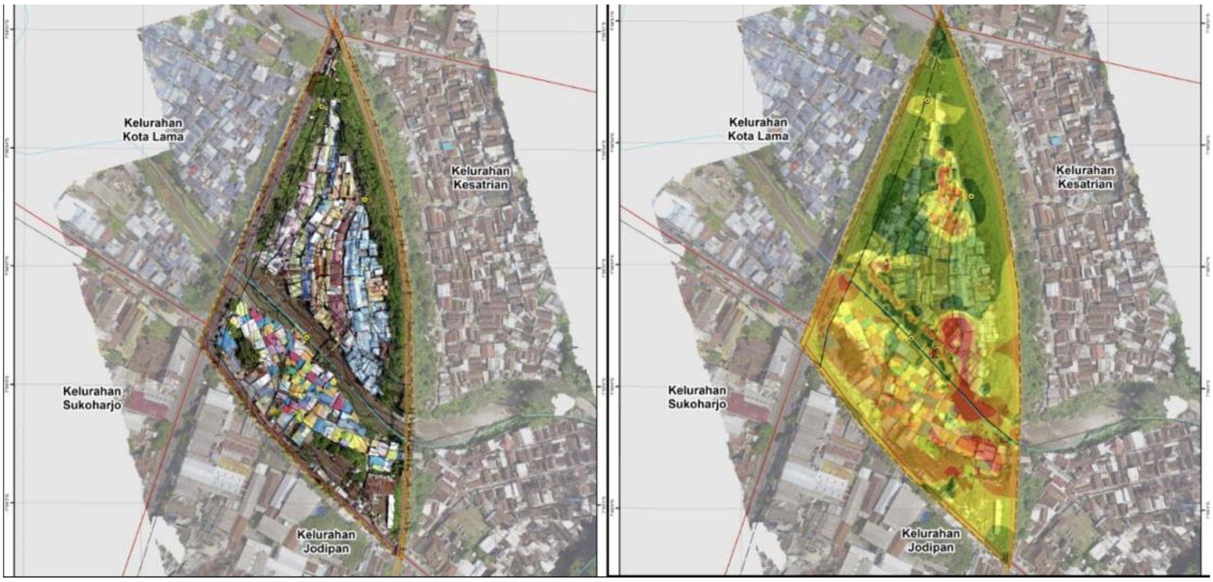

Figure 4. Orthomosaic map of the Jodipan study area

Further analysis of the DSM data revealed several critical slope areas along the riverbank, where natural riparian vegetation has been removed, increasing susceptibility to erosion and small-scale landslides. The flood-risk overlay, when combined with the DSM, identified that numerous informal dwellings are located within medium- to high-flood hazard zones, especially near the inner curvature of the Brantas River. These spatial insights emphasize the urgent need to designate the riverbank as a High Control Zone (HCZ), where land use should be regulated to maintain ecological balance and ensure public safety.

Visual inspection of drone imagery also revealed urban design challenges, including irregular roof growth, narrow circulation paths, and solid waste accumulation near the river edge. These findings highlight the limitations of static urban masterplans that fail to capture dynamic spatial change. By integrating drone imagery with Smart City Planning systems, planners can establish a real-time spatial monitoring dashboard to identify encroachment, evaluate vegetation loss, and simulate restoration scenarios.

4.2 Spatial Findings Visualization and Interpretation

The visualization derived from the drone survey provided an in-depth spatial understanding of settlement morphology and ecological degradation along the Brantas corridor. The aerial perspective clearly shows the compact structure of Jodipan, with buildings tightly arranged and nearly contiguous rooftops forming a continuous impermeable surface. This pattern limits infiltration and accelerates surface runoff toward the river.

At the same time, the images capture the potential of visual transformation and community-led revitalization, as demonstrated by Jodipan's well-known "Rainbow Village" initiative. Although primarily aesthetic, this initiative illustrates the social capital and participatory potential for ecological restoration and sustainable design. Integrating such community-based creativity into a broader environmental governance framework—supported by drone-based spatial evidence—can produce a replicable model of participatory urban regeneration for dense riverbank settlements in other Indonesian cities.

From a planning perspective, the combination of orthomosaic imagery, DSM data, and GIS overlays allows the formulation of adaptive design strategies, including:

a. Reallocation of green buffer zones to restore riparian vegetation along the Brantas River.
b. Redesign of pedestrian corridors to improve accessibility and reduce flooding risks.
c. Implementation of IoT-based environmental monitoring for water quality and waste management.
d. Community co-design programs to transform informal settlements into livable, regulated eco-zones.

The spatial interpretation not only validates the efficiency of drone-based monitoring but also provides a foundation for decision-making in integrating Smart City frameworks with environmental governance at the micro-urban scale. This evidence reinforces the argument that data-driven, participatory planning can balance urban density, ecological resilience, and social inclusivity in developing cities like Malang.

4.3 Integration of Geospatial Data and Smart Environmental Governance

The integration of drone-derived orthomosaics and Digital Surface Models (DSMs) with Geographic Information System (GIS) thematic data provided a multidimensional understanding of spatial and environmental dynamics along the Brantas River corridor. The overlay of topographic, hydrological, vegetation, and land-use datasets revealed critical ecological gaps where green spaces could be introduced or restored. Drone imagery captured micro-topographic variations that are typically undetected in conventional city maps, allowing urban planners to identify potential buffer zones and ecological corridors more precisely.

By combining drone data with IoT-based environmental sensors that monitor air quality, humidity, and surface temperature, the proposed system enables real-time environmental monitoring and automated alerts for urban planners. This integration advances the concept of smart environmental governance by linking spatial data acquisition, digital analytics, and participatory decision-making processes.

Through the conceptual model developed in this study, all geospatial data were structured into a Management Information System (MIS) compatible with Big Data architecture (3Vs: Variety, Velocity, Volume). This MIS framework aligns with Indonesia's One Map Policy (Kebijakan Satu Peta) and the Satu Data Indonesia initiative, ensuring interoperability and transparency across institutional boundaries (Anttiroiko, 2023). The system supports evidence-based decision-making by allowing policymakers to visualize spatial changes and assess policy outcomes in near real-time.

The inclusion of a pentahelix collaboration, involving government, academia, industry, community, and media, proved essential for translating data-driven insights into actionable planning strategies. Through participatory mapping workshops, local residents contributed geolocated information, including informal plot boundaries, drainage paths, and native vegetation clusters, which significantly improved the accuracy of spatial models. This participatory approach strengthened the social legitimacy of spatial interventions and promoted collective ownership of sustainable outcomes (Ansell & Gash, 2008; Bovaird, 2007).

4.4 Design and Conceptual Framework for Riverbank Regeneration

The design framework derived from the spatial analysis phase focuses on adaptive reuse and ecological rehabilitation of the Brantas riverbank. It consists of three integrated intervention layers, each responding to the spatial and environmental issues identified through drone mapping and GIS analysis.

1. Ecological Layer
   This layer aims to restore riparian vegetation and strengthen the ecological buffer along the river. Using drone-based Normalized Difference Vegetation Index (NDVI) and soil moisture data, suitable plant species were selected to form a multi-strata greenery that can reduce surface temperature, stabilize the soil, and enhance biodiversity. Native riparian species, such as Ficus benjamina, Bambusa vulgaris, and Vetiveria zizanioides, are recommended for their resilience and low maintenance requirements.
2. Spatial–Architectural Layer
   This layer proposes restructuring informal housing clusters into organized micro-blocks that maintain community density while improving accessibility, ventilation, and flood resilience. The design incorporates green corridors, bioswales, and vertical greenery systems, which are integrated into building facades and pathways. These strategies aim to balance density with livability, aligning with principles of urban compactness and ecological permeability

Figure 5. Spatial–architectural conceptual plan of reorganized micro-blocks and green corridors

Figure 6. Adaptive Reused and Normalization River

3. Digital Governance Layer
   The third layer integrates environmental data streams into a Smart River Monitoring System (SRMS) connected to the MIS platform. This system allows both authorities and citizens to access real-time data on land-use changes, vegetation health, and waste accumulation through mobile and web dashboards. By linking community reporting apps with official monitoring data, the SRMS embodies a citizen–technology hybrid model for collaborative environmental governance

4.5 Integrated Model for Drone-Informed Smart City Planning

This integrative framework represents a drone-informed Smart City Planning model, where geospatial intelligence, digital data systems, and participatory governance converge to produce sustainable urban design strategies. Technology, in this context, acts not merely as an analytical instrument but as a transformational enabler that bridges ecological data, spatial design, and citizen participation.

In cities like Malang, where land scarcity, informal settlements, and river pollution challenge urban resilience, this model offers a replicable pathway for environmentally intelligent and socially inclusive transformation. The findings also reinforce emerging scholarship highlighting drones and smart technologies as key catalysts in sustainable city management (Yigitcanlar & Cugurullo, 2020).

Ultimately, the study demonstrates how the synergy between drone-based spatial evidence and smart governance frameworks can support data-driven policymaking, ecological restoration, and community empowerment—marking a transition from reactive planning toward predictive, participatory, and sustainable urban management.

5 Conclusion

This study demonstrates the transformative potential of integrating drone-based spatial mapping, geospatial data analytics, and smart governance frameworks in managing and regenerating urban river corridors. The use of drone technology, exemplified by the DJI L1D-20c system, enabled the acquisition of high-resolution spatial data that revealed discrepancies between planned and actual land use along the Brantas River in Malang. The findings highlighted the critical environmental risks posed by informal settlements, including vegetation loss, erosion, and flood vulnerability, underscoring the urgent need for evidence-based spatial planning and real-time monitoring.

By embedding geospatial outputs into a Management Information System (MIS) structured around Big Data principles, the study introduced a digital foundation for smart environmental governance. This MIS aligns with Indonesia's One Map Policy and Satu Data Indonesia initiative, ensuring that spatial information is transparent, interoperable, and actionable. Furthermore, the inclusion of pentahelix collaboration—bringing together government, academia, industry, community, and media—proved essential for transforming spatial intelligence into inclusive planning practices. The participatory mapping activities not only enhanced data accuracy but also strengthened local ownership and the legitimacy of spatial interventions.

The proposed Smart River Regeneration Framework synthesizes three design layers: ecological restoration, spatial-architectural restructuring, and digital governance integration. Together, these layers create a comprehensive model for rehabilitating urban riverbanks through adaptive reuse, sustainable design, and citizen-engaged monitoring. The study concludes that the convergence of drones, geospatial intelligence, and participatory digital governance represents a viable pathway toward environmentally intelligent, socially inclusive, and resilient urban futures—particularly in rapidly urbanizing contexts like Malang. Future research should explore the scalability of this model across other Indonesian cities facing similar challenges of informal urbanization and ecological degradation.

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